

Radiation Damage and Charge Collection Effects in Si(Li) Gamma-Ray Detectors

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ABSTRACT

Si(Li) strip detectors are currently being developed for use in a space-based Advanced Compton Telescope (ACT). To investigate radiation effects, the gamma-ray spectroscopy performance of 6-mm thick planar Si(Li) detectors has been studied as a function of operating temperature and electric field both before and after exposure to a beam of 200 MeV protons. The resolution of the 662-keV peak from a ¹³⁷Cs source was used to monitor the spectroscopy performance of the detectors. The depletion voltage, leakage current, and noise were also monitored. A total of four detectors were exposed to 8.7×10^8 p/cm², two at 88K and two more at 212K. No effects on performance were observed. The latter two detectors were subsequently irradiated at 212 K with an additional 8.7×10^9 p/cm². These detectors did show some resolution degradation. No other effects were observed. The resolution degradation increased at higher operating temperature and decreased with higher electric field. Cycling the detectors to room temperature for 14 hours eliminated the resolution degradation resulting from the high fluence exposure. The resolution of these detectors becomes limited by ballistic deficit and parallel noise in the ~220 K range. A decrease in gamma-ray efficiency, likely due to surface channel effects, has been observed.

Keywords: Lithium-Drifted Silicon, Si(Li) Detectors, Radiation Damage, Gamma-Ray Spectroscopy, Compton Telescope.

1. Introduction

Like germanium gamma-ray detectors, silicon detectors are capable of excellent gamma-ray energy resolution. Silicon must be lithium drifted (Si(Li)) to make detectors sufficiently thick, and operable at a reasonable bias for gamma-ray spectroscopy. However, the rather low Z of silicon and the Z^{4-5} dependence of the photoelectric cross section make even the thickest Si(Li) detectors extremely inefficient above ~100keV. Consequently, germanium is usually the material of choice for gamma-ray spectroscopy. However, a new approach to gamma-ray measurements has recently been conceived that eliminates the need for high Z materials. This is because an incident gamma ray need only Compton scatter three times in an array of detectors in order to give sufficient information for spectroscopy and imaging[1]. Full energy deposition in the detector is therefore not necessary. The elimination of strict reliance on the final photoelectric interaction in the detector makes Si(Li) a viable detector candidate for Compton telescopes. If Si(Li) detectors can be shown to perform well

at much higher temperatures than germanium detectors, the reduction of the cooling power required would make Si(Li) detectors good candidates for large space-borne arrays.

A great deal is known about the effects of damaging radiation on germanium detectors [2-6]. Radiation damage causes hole trapping in germanium detectors. The amount of hole trapping increases with operating temperature and changes with the temperature history of the detector. The hole trapping causes a low energy tail on gamma-ray peaks that can degrade the resolution of the detector. Figure 1 shows an example of gamma-ray peaks measured with a 1 cm thick planar germanium detector that had been irradiated with 7.2×10^8 neutrons/cm², the energy of the neutrons was 183 MeV.[7] Given the drastic effects of radiation damage on the performance of germanium detectors, the question of whether or not the radiation damage characteristics of thick Si(Li) detectors would limit their use in space and at the operable temperature range naturally arose.

While an extensive literature exists on radiation damage in silicon detectors fabricated from high resistivity silicon, little is known about the effects of radiation damage on the gamma-ray spectroscopy performance of Si(Li) detectors.[8] The effects of radiation damage on Si(Li) detectors operated at room temperature and used as charge particle detectors have been studied [9,10]. However, such studies do not cover the much more subtle effects on cooled Si(Li) detectors intended for high-resolution gamma-ray spectroscopy. Furthermore, those studies were performed with relatively low energy (≤ 10 MeV) neutrons, protons and α -particles. These low energy charged particles do not penetrate deeply into the silicon, but rather are stopped near the contacts. In contrast, the much higher energy cosmic rays encountered in a space environment are expected to pass through the detector without being stopped. For this reason the radiation damage effects from low energy particles would be expected to be different than that from cosmic rays. With these thoughts in mind we have studied the effects of radiation damage on the gamma-ray spectroscopy properties of thick Si(Li) detectors.

2. Detector Performance Prior to Radiation Damage

This study was conducted with four 6 mm thick Si(Li) detectors, each having an active diameter of 17 mm. Data is also presented for a fifth detector that was not exposed to any radiation. Two detectors were held in each of the two variable-temperature, liquid-nitrogen cooled, cryostats originally designed for studying radiation damage effects in germanium detectors[11]. These cryostats allow the detector to be stabilized at a particular temperature between 77K and 400K. The four detectors; numbered 8902, 8903, 8912, and 8913, were all fully lithium-drifted and showed full depletion at ~ 350 V bias when measured using 5.486 MeV α -particles at room temperature.

Before the detectors were irradiated, their operational properties were measured throughout the range of operable temperatures. The detectors were each AC coupled to a charge-sensitive amplifier with an 8 nF capacitor and a 500 M Ω load resistor to allow operation at temperatures in the 210 K region where surface leakage currents become significant, on the order of 10 nA. The detectors were tested at 700 V and 1400 V. Leakage currents caused the spectroscopy to be noise dominated in the 220 K region in some detectors. Since no passivation or stabilization material was applied to the

detector surface, the surface leakage depended on the recent history of the detector. In some of the detectors with higher leakage currents, cycling the detectors up to 60°C while pumping on the cryostat sometimes significantly decreased the leakage current. These higher temperature cycles did not change the depletion voltage or the capacitance of the detectors.

The spectroscopy quality of these detectors was good up to ~212K when operated at 1400V using the TC-244 spectroscopy amplifier with a peaking time (T_P) of 4 μ s. The energy resolution for 662 keV gamma rays was 2 keV FWHM or less up to approximately this temperature. However, the charge carrier drift velocities in the 200K region are sufficiently low to make ballistic deficit a problem at the lower bias of 700V. Ideally, longer amplifier peaking times would accommodate the longer charge collection times. Unfortunately, the load resistor needed for AC coupling and the leakage current at temperatures above 200K contribute sufficient parallel noise that the measurements at longer peaking times become noise dominated. The TC-244 pulse-shaping network is relatively unforgiving of ballistic deficit. At one point a 2-pole shaping amplifier was implemented. Although this amplifier better accommodated ballistic deficit it also exhibited higher overall noise at the higher temperatures. Consequently, the TC-244 spectroscopy amplifier was used for the measurements on the detectors that were exposed to radiation (detector numbers: 8902,8903,8912,8913) with $T_P = 4\mu$ s.

Further noise measurements were carried out on a fifth detector (#8906) at 220K. This detector was DC coupled to the charge sensitive amplifier. Ballistic deficit, manifested by gamma-ray peaks being significantly wider than the noise (pulser) peaks, was seen at 700V bias with short peaking times, e.g. $T_P = 2\mu$ s. (See Figure 2) Increasing the bias from 700V to 1200V eliminated the ballistic deficit and improved the gamma-ray resolution, although the noise increased slightly. At longer peaking times of 8 μ s, no ballistic deficit was seen even at the lower bias. (See Figure 3) The system noise was determined by the electronic noise. Further detailed measurements of the performance of Si(Li) detectors as a function of temperature have been made and will be published elsewhere.[12,13]

The gamma-ray peak count rate was found to decrease with increasing operating temperature. Similar effects have been observed in germanium detectors at much lower temperatures, 77-120K [14]. Figure 4 shows the count rate in the 662-keV gamma-ray peak from ^{137}Cs taken with two of the Si(Li) detectors. This effect is attributed to changes in the charge state of the intrinsic side surfaces of the detectors causing the electric field lines to stray toward the surfaces. Charge carriers created in the vicinity of the intrinsic surface will be carried to the surface by the distorted electric field and then move very slowly along the surface to the contact. Consequently, these events will show a large deficit in pulse height. Events that would otherwise be included in the full energy peak are shifted down to energies below the photopeak. The magnitude of this effect increases at higher operating temperature and is measured as a decrease in the count rate of the full energy peak. Although intrinsic surfaces of semiconductor detectors are known to be very sensitive to the residual gases present in the cryostat, there was no visible change in this effect observed in correlation with elevated temperature cycles and pumping on the cryostat. Increasing the bias from 700V to 1400V increases the efficiency ~5-10% throughout the temperature range studied. These effects were observed to be independent of radiation damage.

Of the effects measured here, this loss of efficiency as a function of temperature is the most dramatic, although it is not related to radiation damage. Over the temperature range studied here, there is an approximately 30% decrease in the efficiency of 662-keV peak. However, it should be pointed out that the loss of efficiency observed in the Si(Li) detectors is accentuated by the relatively small diameter of the detectors compared with their thickness, which gives a high surface-area-to-volume ratio. This loss of efficiency should be reduced with larger area detectors. Improvements may also be possible by using different surface treatments in fabricating these detectors.

3. Detector Performance After Radiation Damage

The Radiation Effects Research Station at the Indiana University Cyclotron Facility is capable of providing beams of between 30 and 200MeV protons uniformly over a 7cm diameter area with an accuracy of about +/- 10% [15]. This facility was used to irradiate the Si(Li) detectors to various fluences of 200-MeV protons with the detectors maintained at various temperatures in the cryostats. Detectors 8912 and 8913 were irradiated to a fluence of 8.7×10^8 p/cm² at 88K. The resolution of the 662-keV peak was measured as a function of temperature up to 212K. The noise of the system was monitored with a pulser. The resolution of the 662keV peak with the resolution of the pulser peak subtracted in quadrature, which gives the detector contribution to the overall resolution, is plotted in figure 5. The Full-Width-at-Half Maximum (FWHM) and Full-Width-at-Tenth Maximum (FWTM) were recorded throughout the measurements. The FWTM is presented here because it is a more sensitive measure of charge collection effects. The data in figure 5 was measured with 700V on the detectors. There is no measurable increase in the width of the 662-keV peak in detectors 8912 and 8913 as a result of the irradiation. There is a slight degradation of the detector resolution at the higher temperatures, around 200K, resulting from ballistic deficit effects mentioned above, but the effects were the same before and after irradiation. The irradiation had no other measurable effects on the detectors; there was no change in depletion voltage, no increase in leakage current, and no increase in noise. No changes in these properties were observed after a cycle to room temperature for 17 hours.

Following this irradiation, detectors 8902 and 8903 were irradiated to the same fluence while held at 212K to investigate the possibility of irradiation temperature dependence. Again there were no measurable effects on the detector performance up to 212K. The results from these measurements indicate that for all practical space applications, radiation damage is not the limiting factor for Si(Li) detectors operated at the temperatures studied here.

In an effort to see some radiation damage effect, detectors 8902 and 8903 were irradiated with an additional 8.7×10^9 p/cm² for a total fluence of 9.6×10^9 p/cm². This is a much higher fluence than that expected for any well-chosen orbit. This irradiation was done with the detectors maintained at 212K. At this very high fluence, some damage effects were observed. The only observed effect was a low energy tail on the 662-keV peak similar to the classic effect observed in germanium detectors. Figure 6 shows the 662-keV peak from detector 8902 at 212K before and after this irradiation. The upper energy side of the peak has the same slope as before the radiation damage indicating that one sign of charge carrier is being properly collected as it was before the radiation damage. The lower energy tail reflects preferential charge trapping of either electrons or holes. The amount of tailing

was a function of temperature and electric field. With the detector cooled to 85K, there was no measurable effect from the irradiation. From the plot in Figure 7, the trend of degrading resolution as a function of operating temperature is apparent on detector 8902 at 700V. The effect was clearly measurable compared to the performance of the detector before the irradiation. Operating the detectors at 1400 V decreases the amount of degradation. Cycling the detectors up to room temperature (RT) for 14 hours eliminates the resolution degradation. Subsequent longer cycles to room temperature and to 60°C do not have any additional effect.

The resolution degradation observed at the high fluence level is probably the result of preferential hole or electron trapping. Unfortunately we were unable to determine whether it was hole or electron trapping. Like the hole trapping effects in germanium detectors the trapping increased with higher operating temperature and decreased with higher electric field. However, the amount of the trapping observed in these Si(Li) detectors is far less per incident proton at the temperatures where the effect was most visible. As a general point of reference, rough calculations show that germanium detectors at 87K suffer an order of magnitude more trapping per incident damaging proton than these Si(Li) detectors at 212K. Both the germanium and Si(Li) detectors were operated with electric fields ~ 1000 V/cm. Another comparison made in [16] shows that CZT detectors operated at room temperature show two orders of magnitude more electron trapping than germanium detectors show hole trapping. At 85K there is no measurable radiation damage effect in the Si(Li) detectors even after exposure to the higher fluence level.

In an effort to understand the outcome of this experiment in more detail, calculations of the damage from 200 MeV protons anticipated in silicon detectors were made using the SRIM ion scattering program.[17] A silicon substrate 6 mm thick was used with the ions impinging normal to the silicon surface. At this energy, approximately 24mm of silicon is required to fully stop the protons. Tracks were calculated for a total of 50,000 ions including the full damage cascade of each ion. The amount of damage in the silicon converged to approximately 17.3 vacancies per proton with virtually all (99.99+%) of the ions being transmitted. This is a very minor amount of damage. On the other hand, the greater stopping power of Ge due to its higher Z value leads to significantly more damage from 200 MeV protons. Calculations for a one-centimeter thick slab of Ge show that it suffers damage of approximately 83.6 vacancies per proton. This higher level of damage is consistent with the results obtained here, namely that the performance properties of Ge detectors are significantly more sensitive to radiation exposure than Si(Li) detectors. However, further work is needed to understand on a microscopic level the mechanism of radiation damage in Si(Li) detectors.

4. Conclusion

The performance of standard Si(Li) detectors employing a diffused lithium n-type contact and Au surface barrier p-type contact has been evaluated both before and after exposure to 200MeV protons. At a peaking time of 4 μ s and bias of 700V, the detectors exhibited noise below 2 keV up to approximately 212K prior to being irradiated. Ballistic deficit was seen at higher temperatures under 700V bias with $T_p \leq 4\mu$ s. Operating the detectors at higher bias eliminated this effect. At longer peaking times of 8 μ s, the detector resolution becomes limited by the electronic noise.

Exposure to 8.7×10^8 p/cm², a fluence similar to those expected in orbit, produced no measurable effects on detector performance. Proton doses about an order of magnitude larger were required in order to obtain significant degradation in performance of the detectors. Even at these fluences, the reduction in performance was limited, amounting to a broadening of the ¹³⁷Cs 662-keV line at the higher operating temperatures. The depletion voltage, leakage current and noise were unaffected. Annealing the detectors at room temperature for 14 hours removed even this modest amount of damage. Based on the favorable resolution and noise performance obtained, as well as the fact that they are sufficiently radiation hard, Si(Li) detectors appear to be a very promising candidate for use in the Advanced Compton Telescope (ACT).

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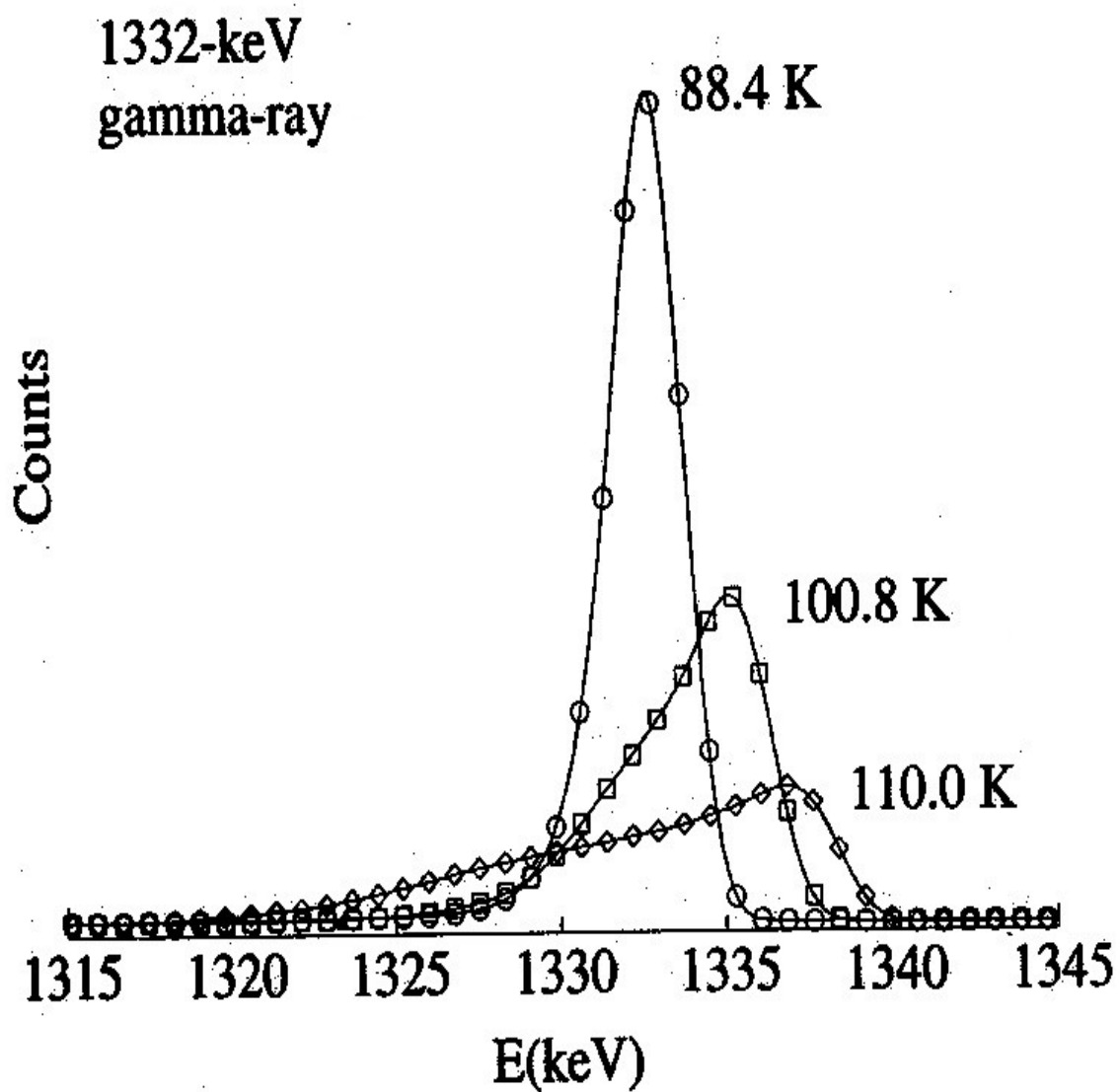


Figure 1 - Photopeak of the ^{60}Co 1332 keV gamma ray in a Ge detector that has been exposed to a fluence of 7.2×10^8 neutrons/cm².

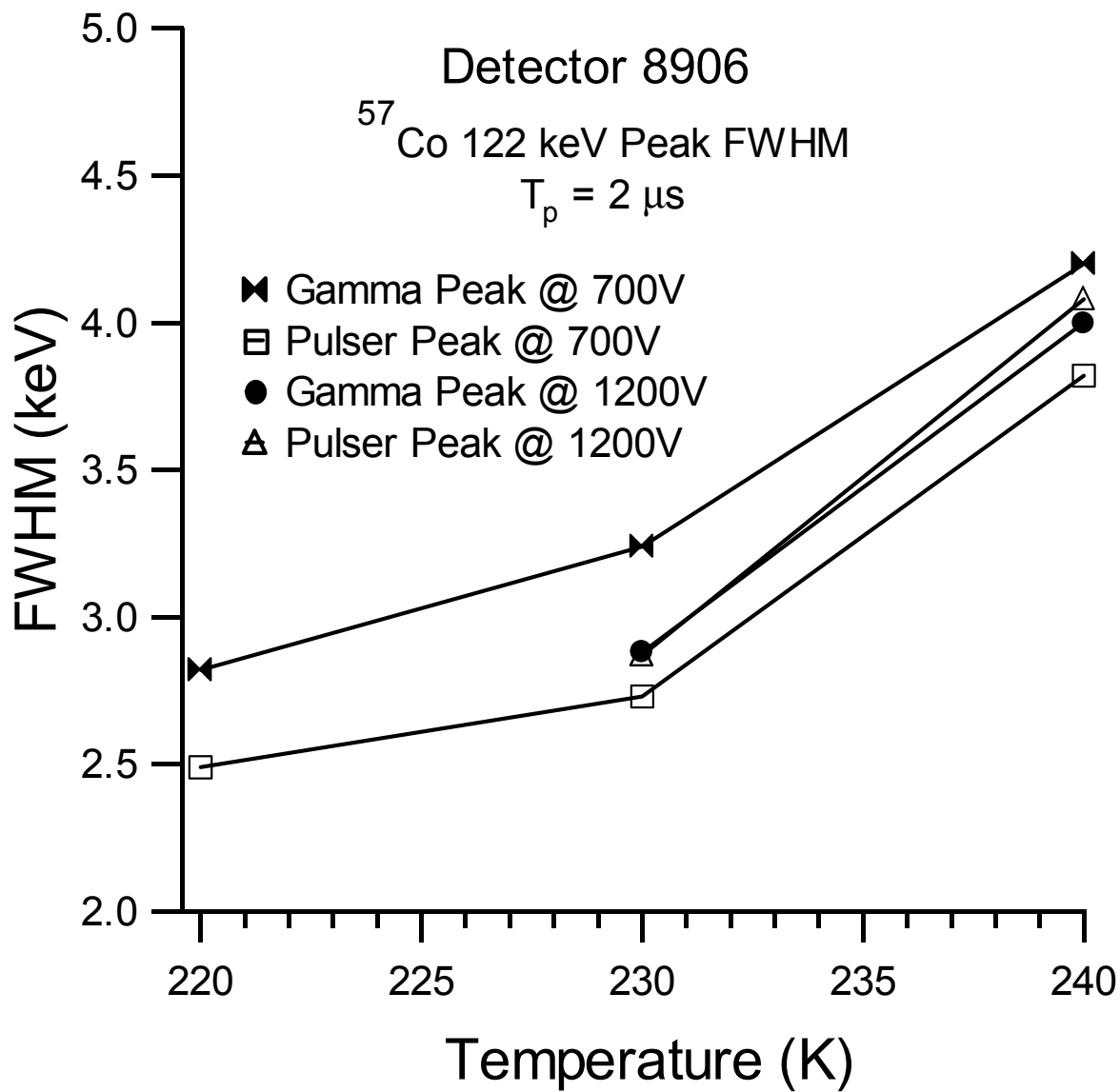


Figure 2 - FWHM of ^{57}Co 122 keV peak vs. temperature and bias at a peaking time of $2 \mu\text{s}$.

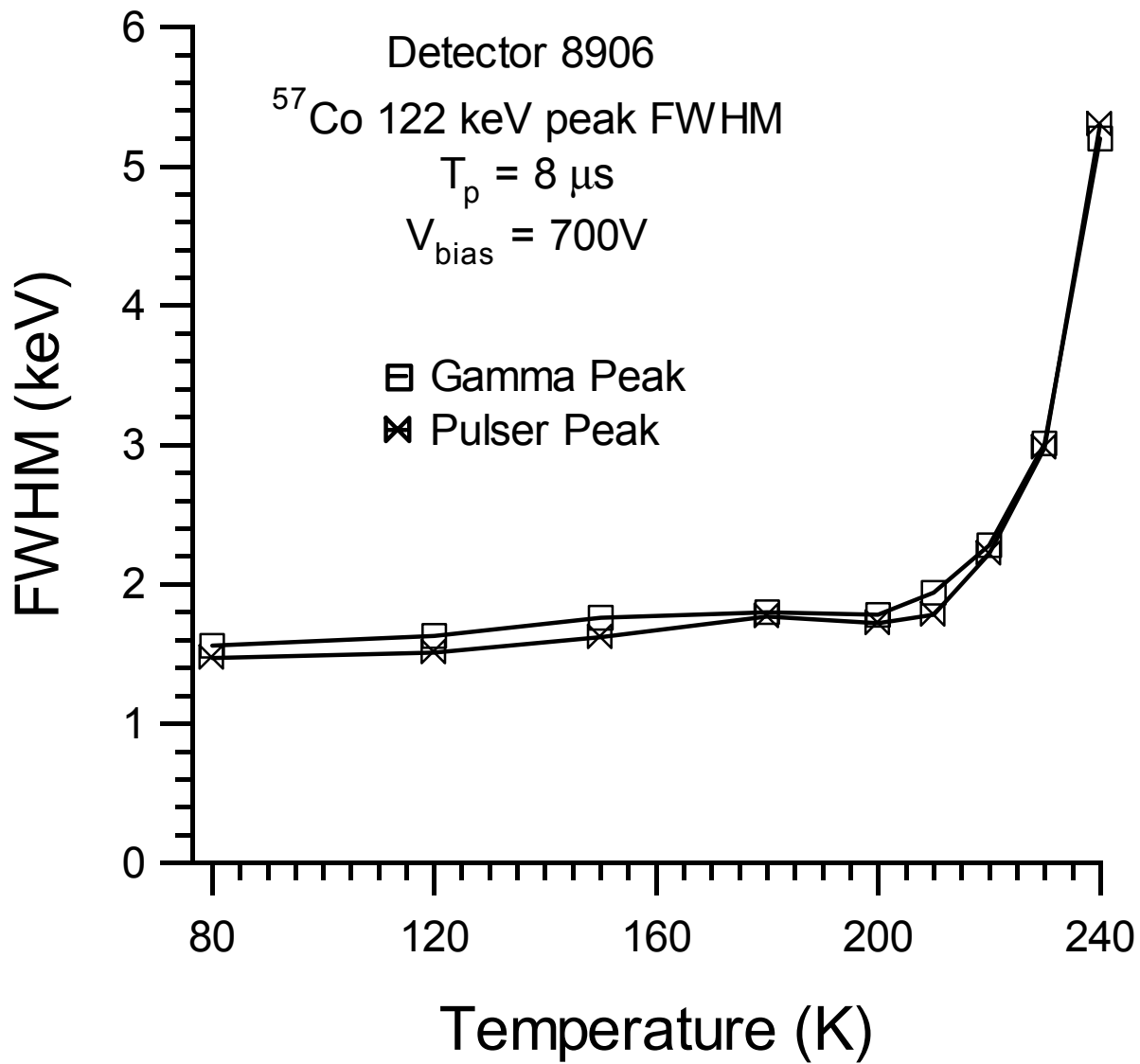


Figure 3 - FWHM of ^{57}Co 122 keV peak vs. temperature at a peaking time of $8 \mu\text{s}$. Bias = 700V.

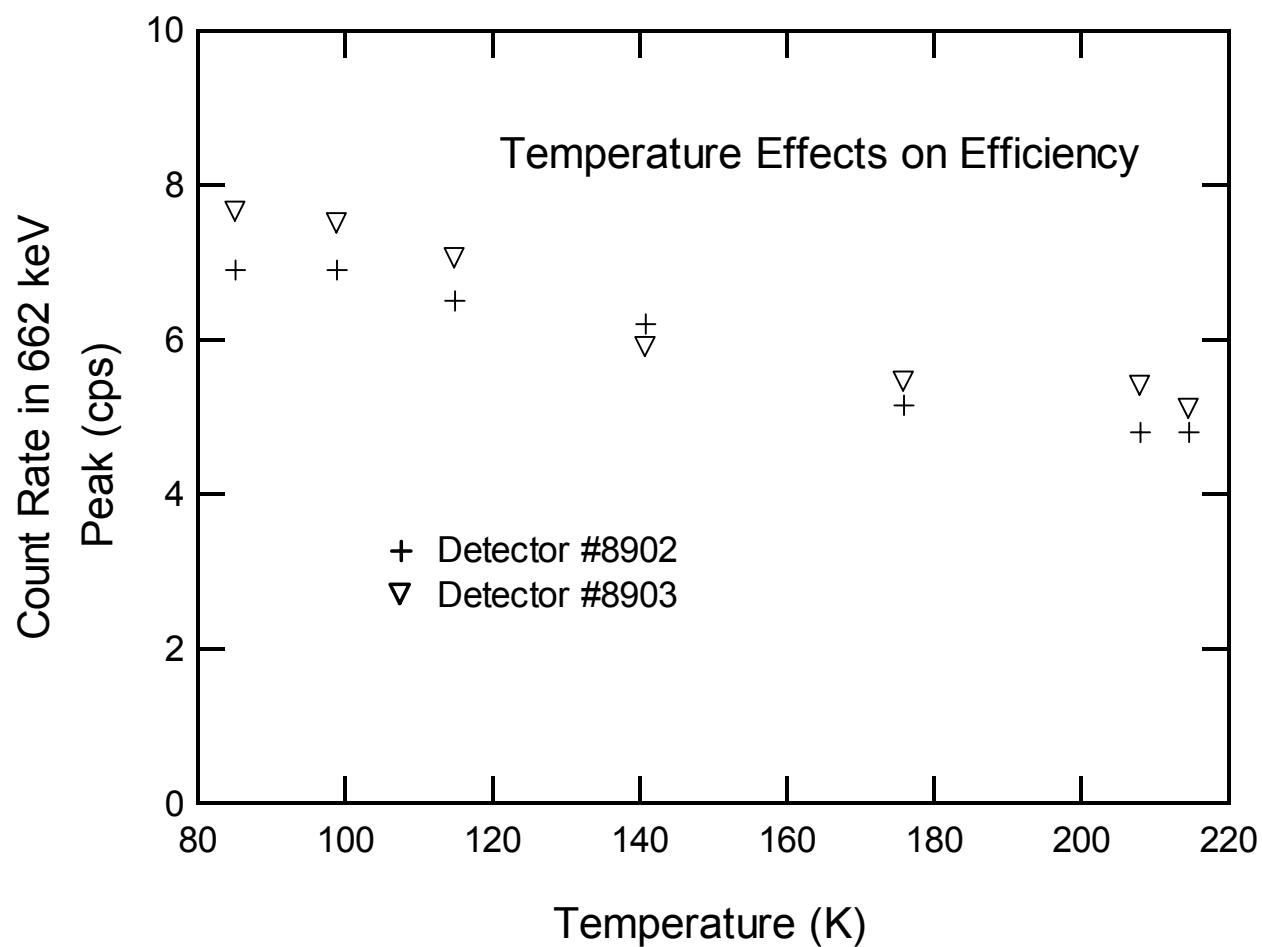


Figure 4 - The photopeak count rate of 662-keV gamma rays of detectors 8902 and 8903 vs. operating temperature. Bias = 700V.

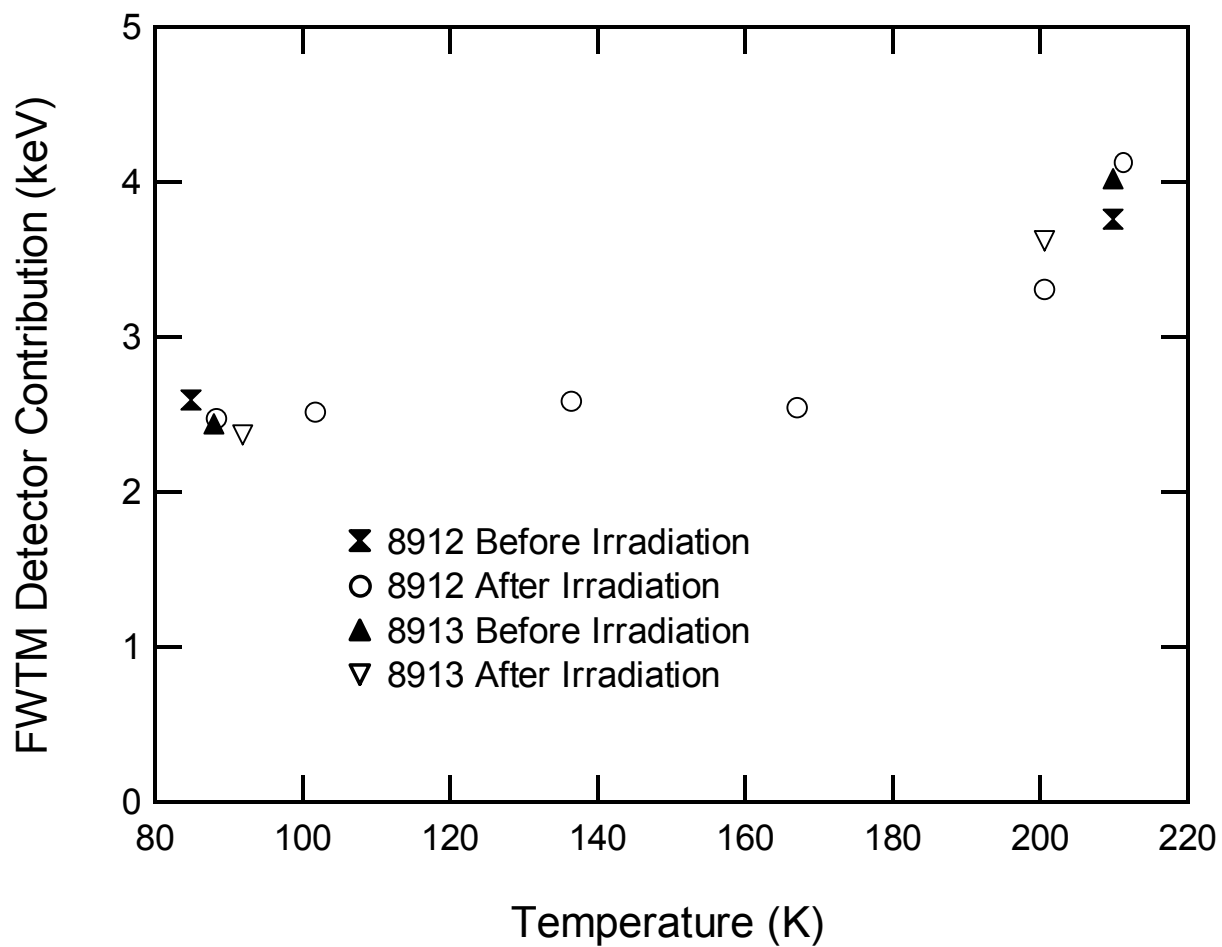


Figure 5 - Detector FWTM before and after exposure to a fluence of 8.7×10^8 p/cm².

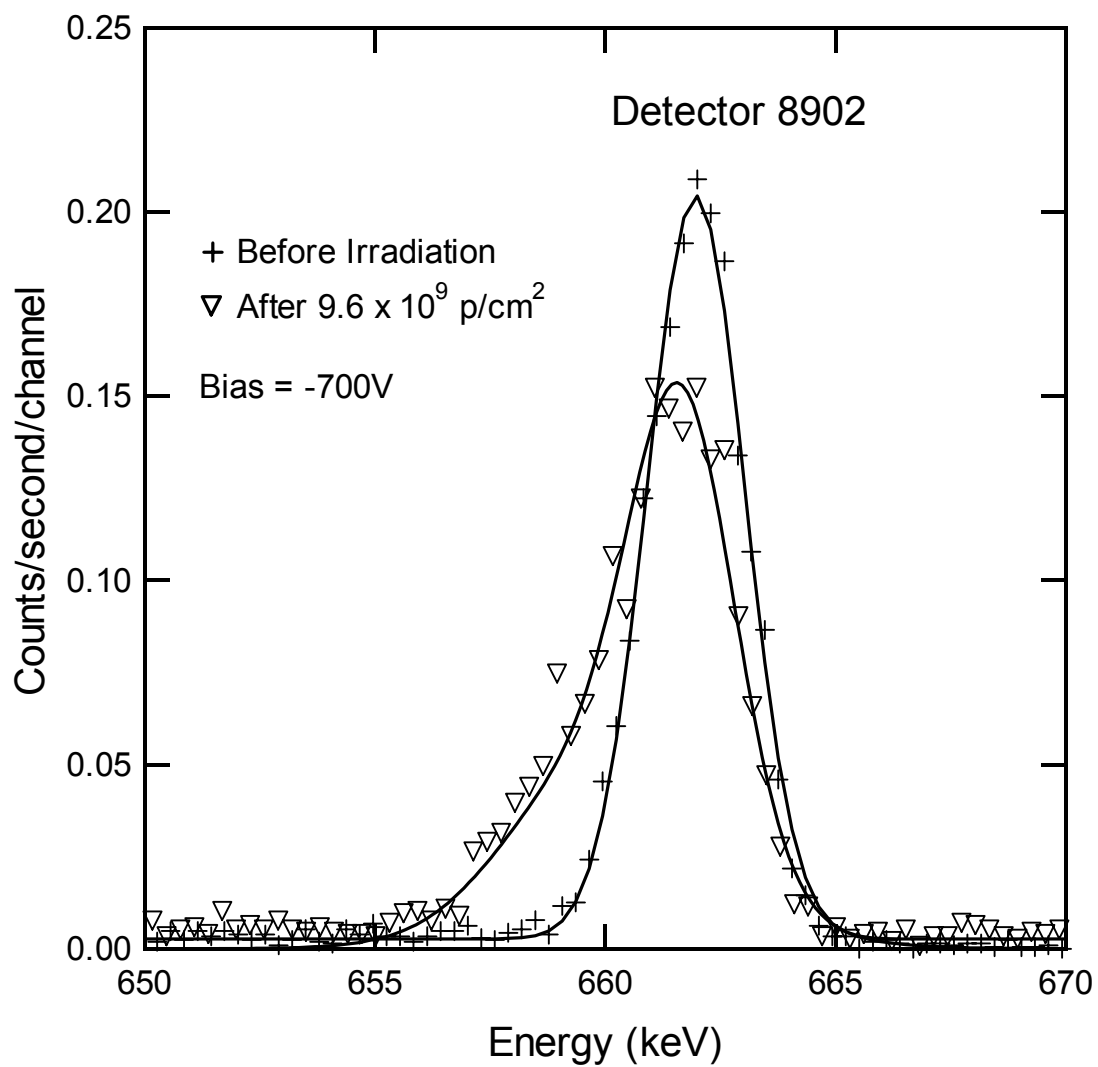


Figure 6 - The 662-keV peak of detector 8902 before and after exposure to a fluence of 9.6×10^9 p/cm².

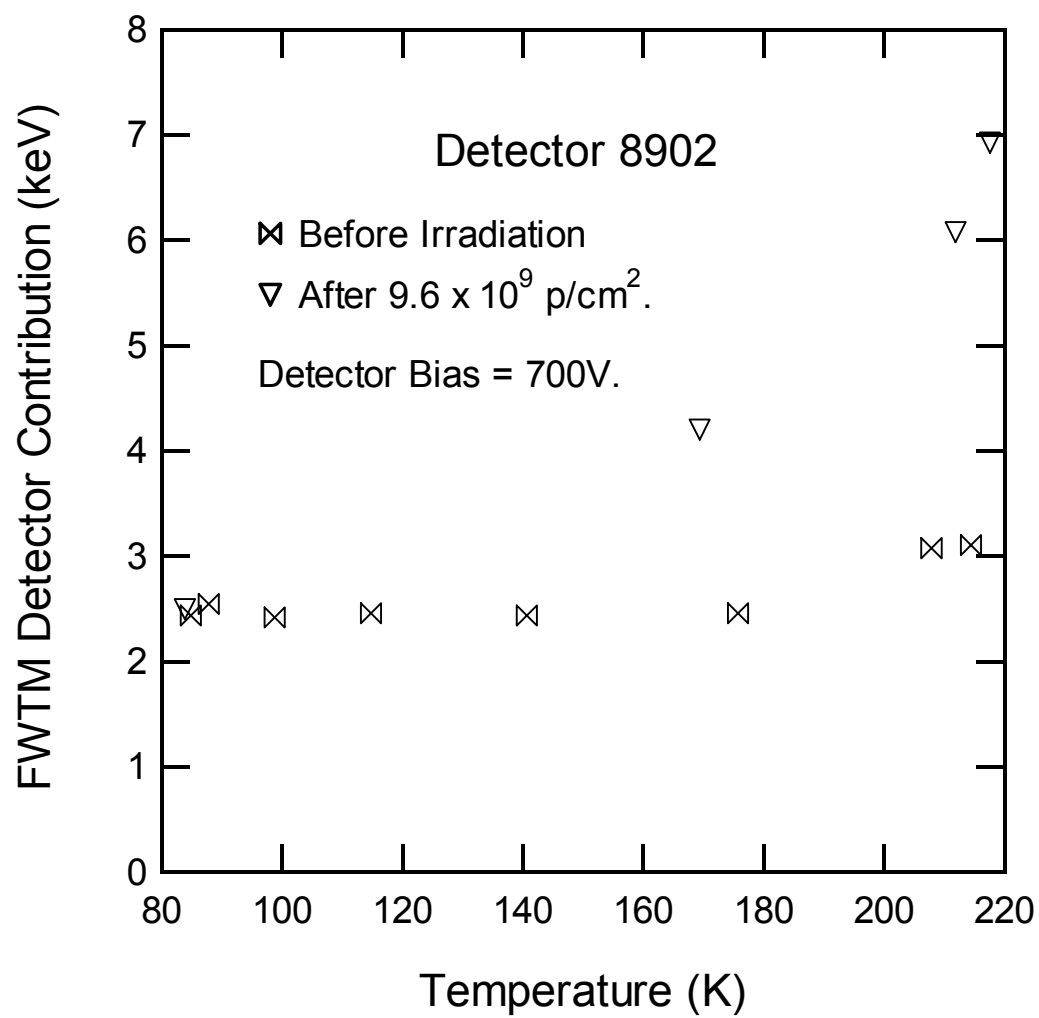


Figure 7 - Detector 8902 resolution vs. temperature before and after exposure to $9.6 \times 10^9 \text{ p/cm}^2$.